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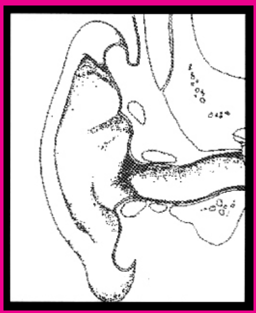

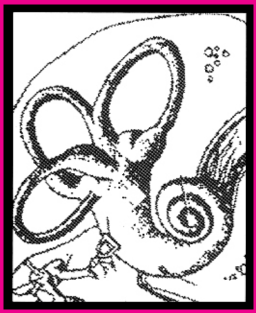

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Auditory distraction and serial memory: The avoidable and the ineluctable

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Abstract

One mental activity that is very vulnerable to auditory distraction is serial recall. This review of the contemporary findings relating to serial recall charts the key determinants of distraction. It is evident that there is one form of distraction that is a joint product of the cognitive characteristics of the task and of the obligatory cognitive processing of the sound. For sequences of sound, distraction appears to be an ineluctable product of similarity-of-process, specifically, the serial order processing of the visually presented items and the serial order coding that is the by-product of the streaming of the sound. However, recently emerging work shows that the distraction from a single sound (one deviating from a prevailing sequence) results in attentional capture and is qualitatively distinct from that of a sequence in being restricted in its action to encoding, not to rehearsal of list members. Capture is also sensitive to the sensory task load, suggesting that it is subject to top-down control and therefore avoidable. These two forms of distraction-conflict of process and attentional capture—may be two consequences of auditory perceptual organization processes that serve to strike the optimal balance between attentional selectivity and distractability.

Keywords: Attentional capture, auditory distraction, changing-state effect, interference by process, selective attention, serial recall

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Introduction

Chief among the characteristics of living organisms is the power of selectivity, the capacity to distinguish those events that are harbingers of opportunity or danger from those that are currently irrelevant for the organism. As with so many such characteristics, these are shown to their most exquisite level of sophistication in mammals. Human hearing is a particularly well-developed sense modality in this regard, made all the more tuned to survival by its capacity to remotely sense events, in the forest as well as on the plain, in darkness as well as in light, hence its epithet "the sentinel of the senses".[1,2] Certainly, there is an argument that the comprehensive processing of the auditory scene is ineluctable, that is, it is obligatory and cannot be prevented via conscious control. It seems then, that whether we like it or not, auditory processing goes ahead, including the organization of sound into streams, when attention is directed away from the sound (for a polemic on this topic[3,4]). How does this ineluctability of auditory processing live alongside the need to bring focal attention to bear on events in other modalities, particularly in an attentional system that has the appearance of having some upper limit to its capacity? A key phenomenal characteristic of attention is that it is limited; there is a focus to which attention is directed, within which events are sharply apprehended, while other events in the person's environment are less clearly part of immediate experience. However, having some analysis of unattended material to hand allows for flexibility-the swift and context-appropriate redirection of the focus of attention-but at the same time it seems likely to incur a cost such as in the time taken up in the selection of possibilities and in the suppression of the unselected alternatives, particularly if the array of possibilities is great.

Although everyday experience suggests that sound intrudes into our mental activities, its impact is perhaps most powerfully and systematically observed through findings from the irrelevant sound paradigm.[5-7] Here, to-be-ignored sound-typically at the level of conversational speech-is presented whilst the person is undertaking a mental task. Usually, the task is presented visually so that there is no possibility of some kind of impairment of performance due to peripheral (sensory) interaction. Despite the fact that it is irrelevant to the visually presented task, the sound can markedly disrupt performance, the presence and degree of disruption varying with the nature of the sound and, for some forms of distraction, the character of the task. In some focal activities, there is an appreciable loss of efficiency. One of these is short-term memory, which typically shows perhaps as much as a 25% loss in laboratory environments. In this setting, physical change in the auditory sequence, but not other factors such as meaning, is one of the key determinants of distraction (but see reports by Buchner and Erdfelder[8] and Buchner *et al,*[9] suggesting an effect of meaning, and a report by Elliott and Briganti[10] that failed to replicate an effect of meaning).

This paper sets out the current thinking on these topics as they relate mainly to memory for sequences. In a related paper from our laboratory,[11] we will address different sorts of memory process, those related to semantic memory that will yield to a similar kind of analysis. As with that other contribution, the main goal will be to try specifying the cognitive processes that underpin distraction. Noise abatement research has sometimes been preoccupied with the level and duration of the sound but our focus is on the cognitive processes underpinning the processing of the sound and whether and how the cognitive character of the task that the person is undertaking influences disruption by the sound. The methods used in this research are ones in which objective measures of performance are taken-it is hardly ever the case that the person is required to offer an opinion of whether the sound is disruptive-on the grounds that subjective reports assume conscious awareness, and since the assumption is that many of the processes we are investigating do not require conscious awareness, a reliance on subjective measures would be problematic.

Chiefly, we use short-term memory tasks to explicate the effects of distraction on cognition. The picture currently emerging from work relating to short-term memory is that there are at least two forms of auditory distraction: *interference-by-process*, produced by a series of changing sounds in which there is a physical change between each successive event (e.g., "ABABABA") and *attentional capture*, brought about by a single unexpected auditory event (e.g., "AAAAAB"). Importantly, these forms are qualitatively distinct inasmuch as the former is not a compound version of the latter. That is, the effect of a sequence of changing sounds is not just the combined effect of a succession of deviant sounds; continuously changing sequences of sounds have emergent properties of perceptual organization or streaming that are not part of the response to a single sound. The defining signature of interference-by-process is that the distraction is not wholly determined by the nature of the sound; rather, it is a joint product of the sound and the particular characteristics of the focal task. In the case of short-term memory, it is the ordering of sound that flows from perceptual organization processes and the ordering of events within the memory task. The more similar these processes are-the more the to-be-ignored sequence affords the same kind of processing as the to-be-remembered sequence-the more control will have to be exercised in producing the correct sequence. Thus, it is important to emphasize that it is not the identity of the items in each sequence that is important but rather the extent to which the to-be-ignored material "fits-in", if you will, with the plan being formulated for producing the to-be-remembered sequence. A key analytic implication of this is that we need a good psychological description of how the brain analyses sound—particularly a well-grounded understanding of how sound is organized—and a refined understanding of the cognitive components of the task; only then can we begin to understand why certain cognitive processes are particularly susceptible to this form of auditory distraction.

Interference-by-Process

There are a large number of cases in which the degree of distraction is determined by the joint action of the irrelevant sound and the nature of the focal task. Here, the supposition is that distraction can be explained by examining the degree of match between the results of perceptual analysis of sound (particularly as it relates to action) and the functional elements of the focal task (again, as it relates to the formulation of action). That is, when the obligatory processing of sound and the focal task both call upon common processes of action formulation, distraction is at its most evident.[12-14] One of the most vulnerable tasks is short-term serial recall in which a list of usually visually presented verbal items (e.g., seven or eight letters or digits) is to be recalled in serial order. In this context, what binds the character of the sound with the character of the task is the extent to which each calls upon similar processes of order encoding.

Perhaps the most compelling evidence for this approach comes from studies examining the way in which the nature of the focal task modulates the degree of distraction. The logic of such studies is to change the demands made on the focal task to be either more or less like what we think to be the way in which the sound is processed and observe whether this influences the magnitude of distraction. Key to the analysis is a proper understanding of what cognitive processes are entailed in the focal task, but the understanding of how sound is processed is also essential to explain the conflict between the two.

A key empirical referent of auditory distraction in serial recall is the changing state effect.[15] This refers to the widely replicated finding that a changing sequence of sound, regardless of whether it is speech or non-speech (e.g., a sequence of different verbal tokens or a sequence of tones changing in frequency), is far more disruptive of serial recall than a repeated or "steady-state" sound (e.g., a repeated token or tone[16]). Clearly, then, change within the sound sequence seems to be one of the key determinants of the distraction. On the face of it, this might be explained by habituation: changing stimuli evoke some kind of orienting response that draws attention away from the focal task, whereas any disruption by a repeated sound soon diminishes as the orienting response habituates through stimulus repetition. Several lines of evidence suggest that this does not happen; for instance, disruption by changing sequences does not diminish as exposure time increases[17,18] (also the section on "Attentional capture"). Rather, continuous change within the sequence appears to be endowed with disruptive potency through its effects on perceptual organization, generically known as streaming,[19] that has phenomenal effects (on the partitioning of auditory objects in time and space) and has important consequences for the encoding of order.

Streaming is best illustrated by a simple example of changing the difference in pitch between tones alternating at speed and noting the changes in perceptual experience. Typically, if the differences are small then the sequence of sound retains its identity as a sound likely to come from the same source, albeit changing in character, but as the frequency difference increases, the sense of "belongingness" to a single entity, or auditory object, if you will, diminishes, so that eventually the experience is of two unchanging streams, one higher in pitch than the other. Modest changes between elements in the sequence allow the coherence and identity of a sound to be maintained, allowing the order of elements comprising the sequence to be reported accurately, but if changes become more extreme—for example, a cymbal, bark, trumpet, gong—then order reporting becomes very difficult.[20]

The general rule is that if change is on a common ground—let us say a person's voice—information about order becomes more strongly encoded as the magnitude of the change increases within the sequence (to some limit at which the changes become too large, at which point identity becomes fragmented and order breaks down). In turn, we find that distraction is modulated as the difference between alternating stimuli is manipulated parametrically. This is shown in Figure 1; it is evident that disruption of serial recall at first rises as the difference between the tones increases, and then diminishes, presumably as the streams break up into two steady-state objects.

By this account, change in the sound is linked with order encoding. Under what conditions does this encoding interfere with the focal task? The interference-by-process account suggests that conflict arises when the focal task embodies processes similar to those automatically deployed in the streaming of the irrelevant sound. It follows that tasks that involve order encoding should, therefore, be particularly susceptible to disruption by sound sequences that also give rise to strong encoding of order. Consider two versions of the same task in which days of the week are presented, one at a time, in a random series but from which one day is missing. In one version of the task, participants are told that at the end of the series, on presentation of a response prompt, they will be required to name the missing day. In the other version, participants are told that at the end of the series, they will be presented with a prompt in the form of one of the days that was presented, and their task is to name the day that came after the prompt day in that particular series. Irrelevant changing-state sound depresses performance on the order-cue version, but not the missing item version. This result can be explained by supposing that the missing item version does not rely on memory for order but rather on awareness of which days appeared in a particular list, whilst in the order-cue version, knowledge of serial order is indeed required. This interpretation is bolstered by the knowledge that articulatory suppression—repeating a word aloud during the task, a tactic known to depress the use of serial rehearsal—markedly diminishes performance on the order-cue version

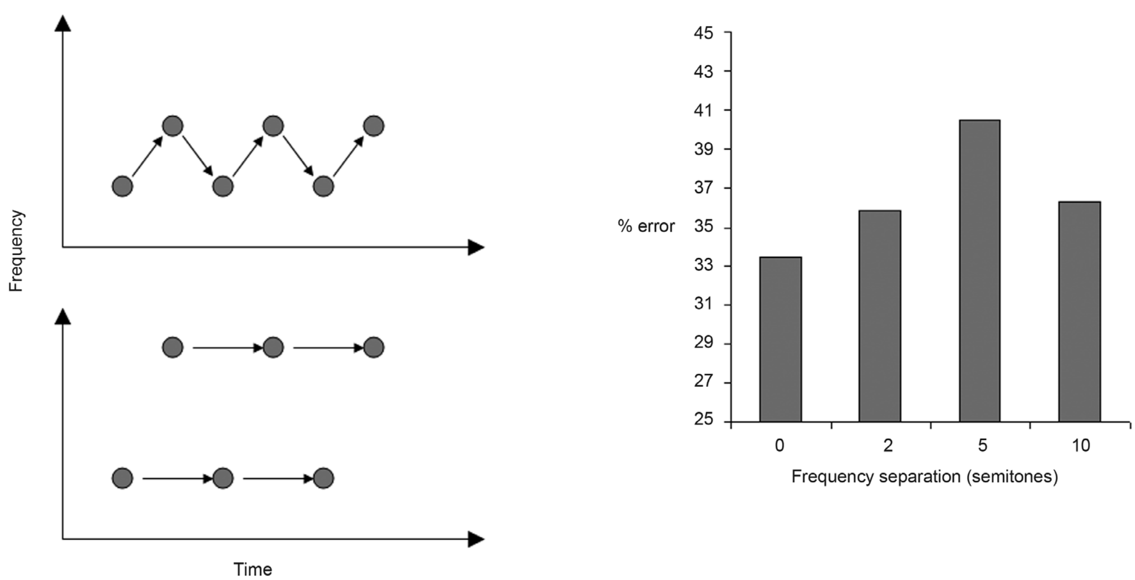

Figure 1: Relationship between degree of change in the irrelevant sequence and the degree of disruption to serial recall. Disruption increases as the difference between successive tones rises above zero, up to a point of inflection which corresponds to the point at which the tones would be organized into separate streams, at which point disruption begins to decrease again[26]

but leaves the missing-item version relatively unscathed.[21,22] So, the focal activity of serial rehearsal seems a necessary pre-condition for changing auditory sequences to bring about distraction. Further evidence for this comes from the fact that blocking serial rehearsal through articulatory suppression eliminates distraction from changing-state sequences.[23]

What is it about serial rehearsal that makes it vulnerable in this way? Although rehearsal by repetition of the to-be-remembered sequence is a covert activity, it can be seen as a plan for motor output, one that is run in "emulation" mode (cf.[24,25]), has the phenomenal character of a "voice inside the head" and from which the final task-appropriate response can be derived (which may, e.g., be spoken, written or typed). In serial recall, the cyclic repetition of the plan has a particular character inasmuch as the words within it are very weakly associated (they are not, typically, constrained by syntax or informed by semantics); so, without the support provided by the activation of the motor plan the transitional probabilities between the words are very low. The transitional information between the words is therefore embodied in the motor plan itself, though this can be modulated by the familiarity of motor acts making up the plan. However, the transitional probabilities are still relatively weak (which accounts for the relatively poor performance in such tasks) and have to be re-visited in the cycle of rehearsal. There will be several occasions on which the rehearsal process will visit an inter-item transition point in a list and little other than the familiarity of it from the first visit to this point may be available to guide which of several alternatives should be chosen as the next in sequence. This flood of transition points makes the repetition of the motor plan vulnerable to disruption from contemporaneous sequences, particularly from changing auditory sequences in which transitional information also figures. The auditory sequence is at its most potent when the number of changes, and hence transitions in the sound, is high (the "token dose effect" cf.[17]) and the physical difference between the stimuli is great (but not so great as to break apart and form several steady-state objects, cf.[26]) while the task is most vulnerable when the similarity of items in the sequence is greatest (where the transitional connectivity amongst the stimulus elements is as probable for remote as for adjacent items). In other words, while in focal attention there is a purposeful attempt to formulate and sustain a unified motor plan, the changing-state auditory sequence presents frequent signs that a new auditory object could be part of the auditory scene and hence be in contention for a shift in attentional focus.

Evidence is beginning to emerge that other types of sequencing activity are prone to disruption by changing-state irrelevant sound. It is well-established that infants and adults (and some non-human animals) learn the statistical regularities of linguistic and non-linguistic stimuli[27-29]). Disruptive effects of irrelevant sound sequences can be observed using a test that taps the statistical learning of non-verbal stimuli.[30,14] This is an important outcome in many senses; it is one of the few demonstrations of irrelevant speech effects with spatial stimuli,[31] a finding that does not favor any theory that restricts this type of distraction to verbal stimuli (such as the one based on the phonologic similarity of the sound to the to-be-remembered material[32]).

The detail of how this works is not clear; is it the price to be paid for suppressing a somewhat unstable auditory object that may be about to change its object status? Certainly, there seems to be evidence of inhibition of the unattended sequence; if the irrelevant sequence is reintroduced on the immediately subsequent trial as a to-be-remembered sequence, it is less well recalled than a novel sequence (which contains the same items but in a different order[33]). Or is it the involuntary re-direction of resources from the focal task? Recent evidence suggests against the latter explanation. On the "re-direction of resources" account, increasing the amount of processing resources required to perform the memory task by making the to-be-remembered stimuli more difficult to perceive should attenuate the likelihood of resources being drawn involuntarily to the sound. Contrary to this prediction, the magnitude of disruption caused by changing-state auditory sequences does not change under greater focal-task load.[34,35] Moreover, the re-direction of resources account is ill-equipped to deal with the finding that the disruption is specific to serial memory; tasks just as difficult—consuming similar degrees but different kinds of processing resources (e.g., the missing item task described above)—appear to be immune to the changing-state effect. Clearly, there is something highly specific to serial processing that is susceptible to impairment.

Attentional Capture

Recently, emerging evidence suggests that interference-by-process is quite distinct from another form of distraction, namely attentional capture. Typically, attentional capture arises when a single deviant event, say a change of voice, is embedded with an irrelevant sound sequence.[36,37]

There is a body of work examining psychophysiologic responses to a deviant auditory event following a repeated "standard" sound (the "oddball" paradigm) that has contributed substantially to our understanding of selective attention and how unexpected auditory events may recruit processing resources.[38,39] However, typically (but not universally), the oddball paradigm does not involve a focal task, rather the participants are at rest. Studies from our laboratory have used memory tasks, including serial recall, as the focal task and measured the impact of deviant stimuli on performance[40] without also taking psychophysiologic measurements.

In the studies of Hughes *et al,*[36,37] rare and unpredictable changes in the rhythm or voice in which an auditory irrelevant sequence was presented diminished serial recall appreciably. The pattern of results is interesting, not least in that it differs from that found with changing-state auditory sequences. Perhaps one of the most notable is that the deviant effect is only apparent during the "study" phase of the serial recall task. In serial recall, it is usual to distinguish two main phases of the task prior to retrieval: the study or "presentation" phase during which the visual items are presented, and the "rehearsal" phase during which nothing is presented but the participant is expected to sub-vocally rehearse the list. Of course, rehearsal is common to both phases; the presentation phase will require rehearsal of just-recently-presented items but encoding is restricted to the presentation phase. So, the rehearsal load builds up to its maximum at the end of the list and remains at a fairly static level until the end of the rehearsal phase at the point when output is produced. The changing-state effect follows this pattern of load, disruption being slightly less at the early stages of list study and becoming maximal during the rehearsal phase.[4142] Of course, such an outcome is completely in line with the research we reviewed above, showing that rehearsal in the focal task is a necessary pre-condition for the changing-state effect; so, we might expect that the degree of disruption would ebb and flow with the dependence on serial rehearsal. For deviant sounds, however, the disruption seems to be localized to the encoding phase; it is not found when the sound is confined to the rehearsal phase.[36] This suggests strongly that the attentional capture brought about by a deviant acts on the intake of information while the changing-state effect acts through motor planning processes.

Further evidence of the distinct character of the deviant effect and the changing-state effect comes from a comparison of their action with the missing item and serial recall tasks, with deviant effects observed on both but changing-state effects shown only on the serial recall task.[37] Moreover, deviant effects have been found with a range of other non-order based tasks such as speeded classification tasks,[43,44] and cross-modal Stroop.[45]

Recent experiments in which the difficulty of encoding in the focal task was manipulated have also reinforced the distinction between the two forms of distraction.

Making the intake of information more difficult—degrading the quality of the to-be-recalled digits so as to make them difficult to read—eliminated the damage to performance produced by a deviant but, as we reported above, the changing-state effect is not modulated as the difficulty of encoding the task changes.[34] The dissociation between the deviation effect and the changing-state effect in response to increased encoding load also helps to adjudicate between two accounts of why the deviation effect is diminished under high load. One possibility is that the sensory processing of the irrelevant sound is gated—and hence the deviant goes undetected—as a passive by-product of the higher perceptual load imposed by the focal task (cf. Lavie's [35] perceptual load model of attention). However, on this sensory gating account, it is difficult to explain why the changing-state effect is immune to the same increase in load. Instead, we suggest that the attentional capture mechanism that we think is responsible for the deviant effect is subject to a top-down blocking process (cf.[46]). Based on this view, the sensory processing of the sound and the detection of the deviant proceeds as normal but the attention switch to that deviant is resisted (for further evidence for a functional distinction between deviance-detection and an attention-switch to the deviant,[47,48]). In this way, the immunity of the changing-state effect to increased encoding load is no longer so mysterious; based on the view that the changing-state effect is not due to attentional capture but rather due to corruption of the process of serial rehearsal, a capture-deactivation process would not be expected to preclude this form of disruption. One current strand of work in our laboratory is concerned with finding convergent means of studying this top-down resistance-to-attentional-capture by, for example, assessing whether foreknowledge of an upcoming deviant attenuates its deleterious effects on short-term memory and other attention-demanding tasks (cf.[46]).

The picture on the action of deviants and sound sequences is gratifyingly consistent: Auditory deviants seem to have effects generally, that is, ones not restricted to a particular class of task, the effect most probably arising during the encoding of material, and the impact of changing-state stimuli being very highly specific to serial motor planning. This is not to imply that in everyday terms, the breadth of application of the changing-state effect is narrow; serial recall is often regarded as a close analog to the primitives of language production, so it seems reasonable for results of this form of distraction to be applicable to a wide range of settings involving ordered behavior, including the learning and use of language.[49]

At the same time, these results further bolster the view that the changing-state effect is not related to habituation of capture effects from individual stimuli; individual-item effects and sequence effects seem to be functionally distinct. Several theories suppose that the changing-state effect is due to attention being drawn away from the focal task.[50-52] For example, as part of the *embedded process model* of short-term memory;[42,50,53] suggested that changing-state sequences were more disruptive than a steady-state sound because the change kept evoking capture, whilst with a steady-state sound, repetition resulted in habituation of the capture response. This type of theory is weakened by the recent results reviewed here. We have already noted that extended presentation of irrelevant sound does not only alter the magnitude of the changing-state effect (above) but also increases the effect as the rate of presentation of the sound tokens increases rather than being diminished as would be expected from an habituation account (the token dose effect[17] for related phenomena under the heading of "token set-size",[12]).

Is Sound Disruptive Because We Cannot Avoid Deliberately Directing Attention to it?

The extent to which the irrelevant sound in these paradigms remains truly "unattended" (up to the point at which attentional capture occurs in the case of a deviant), and perhaps instead subject to deliberate processing, has been a constant source of anxiety for researchers. Until recently, the fact that distraction is not diminished when the content was relatively more interesting (say, narrative speech compared to the same speech reversed, cf.[6])—and hence arguably more likely to draw deliberate attention—was sufficient reassurance. Recent work has been helpful in showing that the impact of changing-state sequences at least is associated with a passive, obligatory, mode of auditory processing, not an active, deliberate listening, mode.[54] The study comprised two stages: the first established the efficiency with which participants could judge accurately a match between two six-tone sequences. In one version of this test, the judgment could be made passively, the difference between the two sequences was brought about by changing a single tone, all other tones remained unchanged. This version of the task could be accomplished by passive global pattern matching.[55] In the other type of sequence, the comparison sequence was shifted *en masse* in frequency by several steps, but the relative frequency of the tones within it stayed the same, thereby preserving the melody. Differences in the two sequences were then produced by changing a single tone in order to disrupt the melodic sequence. This version necessarily requires active recoding of the sequence in order to detect if the "melody" is retained across frequency ranges in the two sequences (Figure 2 for a schematic depiction of these tasks). The requirement to concurrently engage in task-irrelevant articulatory activity, thereby impeding this active recoding, rendered participants unable to perform this second sequence matching task, while they were still able to perform the passive version at an above chance level. In the second stage of the experiment, the tone sequences used in the first stage were used as irrelevant sound stimuli during a serial recall task. The participants' capacity to do this task and the extent to which performance was disrupted by the irrelevant sound was correlated with performance on both auditory sequence processing tasks. While the task requiring deliberate sequence processing positively correlated with performance on the serial recall task, it did not correlate with the degree of disruption caused by the sound. However, the task measuring more passive, obligatory, sequence processing did positively correlate with the extent of disruption. In other words, the better participants were at the passive sequence processing task, the more disrupted they were by irrelevant sound. This result indicates that it is the type of auditory processing that may be accomplished in an obligatory, rather than a deliberate, mode of processing that is responsible for interference from changing-state auditory sequences.

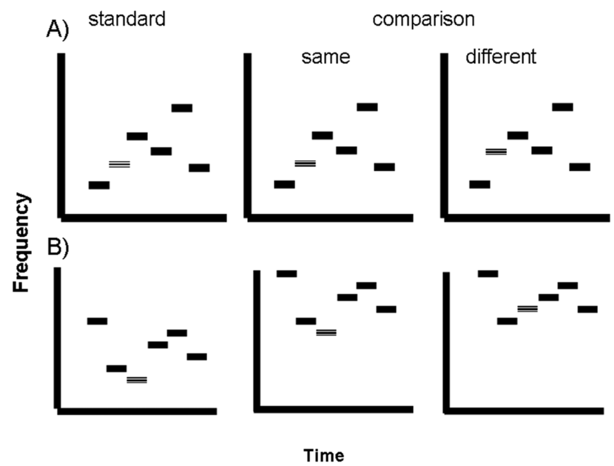

Figure 2: Schematic depiction of the sequence matching tasks used by Macken *et al*.[54] Panel A shows a same and different trial for the obligatory, global pattern matching task, while Panel B shows an example of the type of stimulus used in the deliberate, recoding version of the task. Short-term memory is a serial order memory component of working memory (which usually entails some kind of manipulation of the verbal materials in short-term memory not necessarily involving serial processing). Mental arithmetic might be a working memory task.

Task Memory Load and Distraction

The role of memory load in shaping auditory distraction is poorly understood. We have quite strong indications that perceptual processing load plays no role in the changing-state effect (though an important one in capture of attention by deviants[34]). Some have suggested that perceptually loaded tasks and memory-loaded tasks behave in different ways. While perceptual load decreases the likelihood of distraction, memory load increases it: "Load on executive control functions, such as working memory, that renders them unavailable to actively maintain stimulus-processing priorities throughout task performance has the opposite effect to perceptual load: it increases interference by irrelevant low-priority distractors rather than decreasing it."[35]

One approach to assess the possible impact of memory load on auditory distraction might be to manipulate load parametrically by, say, presenting sequences of different lengths and observing the effect of distraction as the list length increases, on the presumption that "memory load" increases also. This may not be a successful strategy, however; participants tend to keep the size of the rehearsal group roughly constant as the length of the list increases (the number correct does not increase as the length of the list presented to the participant goes up). Additionally, there may be changes in strategy as the list length changes.[56,57]

Given the difficulties associated with manipulating memory load experimentally, another way in which the issue may be addressed is by examining whether individual differences in short-term memory span—used here as a proxy for memory load—correlate with susceptibility to auditory distraction. Although the body of work on this topic is not great, the evidence suggests that the effect of memory load on auditory distraction is insubstantial. In relation to the changing-state effect, memory load *per se* does not seem to interact with the degree of distractibility. Consistently, there has been a failure to find a correlation between short-term memory span and susceptibility to the effects of changing-state sound.[58-61] However, there are some instances of a significant correlation between selective attention and memory span; Conway *et al,*[62] found that individuals scoring highly on an operation span measure[63] are less likely than low span individuals to detect their own name in the unattended channel of a dichotic listening task. However, Beaman[58] in a series of studies using operation span, found no correlation between span and the impact of changing-state sound.[64] Nevertheless, Beaman[58] did find a negative correlation between operation span and the number of intrusions from the irrelevant sequence in a category clustering task—a task that has a seriation component but whose performance is largely based on semantic processing of the list—which suggests in turn that the detection of one's own name in the dichotic listening task, is related to semantic processing, not serial order processing. Moreover, Sörqvist[64] recently found that operation span also correlates negatively with susceptibility to the disruptive impact of a single deviant sound during serial recall.

Summary and Concluding Remarks

Research on auditory distraction in the context of serial short-term memory points strongly to the conclusion that such distraction comes in (at least) two qualitatively distinct forms. For one of these forms—interference-by-process—the qualitative nature of the focal task is critical to the disruption: The obligatory order encoding of continuously changing sounds conflicts specifically with the similar but deliberate order processing demanded by the focal task. This disruption of serial short-term memory by changing sounds is ineluctable for two reasons: first, the processing of order in changing-state sound appears to be obligatory[4,54] and, second, it is the very act of engaging in serial rehearsal to perform the serial memory task that renders it vulnerable to that obligatory processing.[23] In[11] we suggest ways in which this unavoidable interference-by-process seems to be applicable also to other settings, particularly semantic-based (as opposed to serial order) tasks, where in this case it is the obligatory processing of the meaning of irrelevant sound that assumes potency. Two key characteristics of a second form of auditory distraction—attentional capture by an unexpected deviation in the irrelevant sound—distinguish it from interference-by-process: its task-generality and its avoidability. It is general insofar as the impairment is not dependent on the particular qualitative characteristics of the focal task[37] and evidence that it is avoidable comes from the finding that under difficult encoding conditions the capture response can be brought under top-down control.[34]

Whilst we have tended to focus here on the functional distinctions between interference-by-process and attentional capture, it is important to recognize at the same time that both forms of auditory distraction seem to be the result of the obligatory processing and organization of the auditory sequence. Even the effect of a single deviant sound appears to be the product of an initially preattentive analysis of the prior sequence inasmuch as the detection of the deviation that leads to attentional capture must, logically, be based upon an analysis of the difference between the deviant and its precursors.[37,38] Thus, whilst the mechanism of task disruption differs ultimately, both forms of disruption may constitute different sequelae of the same preattentive streaming process. The involuntary order encoding that mediates the changing-state effect seems to result from perceptually integrating sound tokens that are acoustically different to one another but are still similar enough to be perceived as changes on a common ground.[26] In contrast, attentional capture by a deviant seems to occur when a single auditory event is so distinct that it cannot be assigned to the same stream as those comprising the prevailing sequence and hence will, as a new "object" on the auditory scene, require evaluation as to its potential significance for ongoing behavior.[37]

What these phenomena and theoretical considerations tell us about the place of attentional control more generally, particularly, as it relates specifically to speech perception and production, is beyond the scope of this article. However, some general remarks about the importance of the control of action in understanding the foregoing research may be fitting. Our explication may, however, require some suspension of disbelief from the reader—particularly a reader familiar with the received view of how short-term memory works—since it involves reconstrual of short-term memory as a system for motor planning that has memory-like qualities, rather than strictly as a "memory" system. The action-control perspective suggests that as to-be-remembered sequences are encountered, they are loaded onto a motor plan. This plan may be thought of as an abstract skill for verbal sequence production, being populated by particular gestures that correspond to the items in the sequence. The plan is used to carry and sustain the information for the to-be-remembered sequence until the individual is cued to make the sequence manifest (the form of the output can be vocal or manual, of course, but the substrate from which these draw is a vocal-gestural plan).

The basis of this "motor-memory-system" view of short-term memory is the motor control system and, in particular, the way it deals with feedback. Classically, ideas about the control of action relied on the idea that sensors in the limbs feedback the information to a controller about how much an action had progressed toward a goal. The controller then sends further commands to the limb to bring it closer to the goal from which further feedback is derived, and so forth in a continuous cycle. Contemporary perspectives of motor control acknowledge that this type of mechanism is too slow and error-prone to account for highly skilled motor behavior. Instead, it has been suggested that feedback comes from a model of the body that is in the brain, one model that is continually updated on the basis of experience. The key advantage of such an arrangement is that it does not suffer the delays inherent in a system requiring feedback from the limbs.[65] Indeed, this model can be run without implementing any motor action—in emulation mode—so that the person can experience the action without the limb producing it.[24] Reading to oneself is just such an emulation-mode action, it has all the trappings of speaking aloud but the voice is an "inner" one. Our view is that short-term memory tasks involve repetition of the to-be-remembered sequence and that many of the errors in the reproduction of the sequence are due to problems with the motor planning process.

The inchoate nature of the plan in short-term memory tasks also makes it vulnerable to being overtaken by competing plans. Reciting "Mary had a little lamb" to oneself is not vulnerable because the links between parts of the plan are already established and the elements, as well as their order, are predictable. Letters or digits in meaningless combination, the usual material for short-term memory tasks, are held together by the motor plan alone and are therefore particularly vulnerable to disruption. In this article, we discussed ways in which potential motor plans borne of auditory perception can interfere with the motor plan used purposefully to sustain memory for sequences. We attempted to show that some types of distraction are avoidable but that some are also ineluctable.

Finally, a note on practical implications is given below. Alas, there seems to be no straightforward generalization, except perhaps that the level of the noise is not that important. For some types of noise, particularly, if the sound contains sequences of changing stimuli like speech, there will be an unavoidable effect of noise. But this depends on the task; if that too involves sequence processing, then performance deficits of up to 30% may be expected. Sequence processing of this sort is widespread in information-rich and safety critical systems (e.g., process control rooms, aircraft flightdeck). However, the remedy by way of abatement is not simple: Noise will have either to be made inaudible (which is not usually practicable, even for noise of modest intensity) or the changes will need to be masked (which involves introducing more sound into the work environment, which might lead to unfortunate effects of masking[66]). Our research suggests that single short stimuli, though more universal in terms of the type of mental activity they influence, are more susceptible to the prevailing context in which the sound occurs. Specifically, such stimuli capture attention under normal load, but it appears that their "call for attention" can be deliberately ignored if the conditions either allow (with foreknowledge of the upcoming deviant[46,67]) or make it necessary to do so (e.g., when the processing demands of the focal task are high[34,68]). The key message of our review is that auditory distraction can only be understood in terms of the way that the brain processes sound and the details of the way that our cognitive system processes the focal task. The result is inevitably rather complex, but this should be unsurprising given the nature of sensory and cognitive processing.

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